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Description of the tests. All tests discussed below were conducted the following equipment, conditions and materials: permeameter meter is 1·5 m (5 ft); water pressure is 200 or 400 kPa (4000 or 8000 ı soil hydraulic conductivity is of the order of 10^{-7}–10^{-6} m/s (10^{-5}–10^{-4} s); soil thickness is 0·45 m (1·5 ft) (except in the few tests conducted an earth cover); the geomembrane is a 1 mm (40 mil) thick PVC geom brane; the geotextile is a polyester needlepunched nonwoven mat (mass per unit area 450 g/m^2 (13 oz/yd^2), 4 mm (160 mil) thick, hydraulic conductivity 0·001 m/s (0·1 cm/s) under no compressive str

Scope of the tests. Fukuoka conducted a few tests with an earth cove top of the geomembrane. These tests showed a small leakage rate re tion compared to the case without earth cover. However, no u quantitative conclusion can be drawn because the effective stress du the earth cover was very small compared to the water pressure. In the ı discussed hereafter, there is no earth cover on the geomembrane. main interest of these tests is to provide an evaluation of the effect geotextile on the leakage rate.

Tests with geomembrane alone on soil. Fukuoka's tests with no gec tile between the geomembrane and soil show that: (i) the leakage ra less than the leakage rate through soil alone when the geomembrane diameter is less than approximately 20 mm (0·75 in); and (ii) the leal rate becomes equal to the leakage rate with no geomembrane at all w the diameter of the geomembrane hole is larger than approxim 20 mm (0·75 in). This indicates that in the latter case, leakage fi laterally between the geomembrane and the soil and reaches the wal the permeameter (diameter 1·5 m (5 ft)). This is confirmed by pres measurements in the soil which show that the full water pressure is apr on top of the soil. In other words, the geomembrane is uplifted and w flows freely in the space between the geomembrane and soil.

Tests with geomembrane on geotextile on soil. In these tests, the gec tile had no hole (only the geomembrane had a hole). Also, the geote and the geomembrane were not glued together (i.e. the geomembrane simply laid on the geotextile). This detail will be important in the dis sion presented subsequently.

These tests show that: (i) when the geomembrane hole diameter is than 50 mm (2 in), using a geotextile under the geomembrane decre the leakage rate by approximately one order of magnitude or m compared to the case without a geotextile; and (ii) when the geomemb hole diameter becomes larger than 100 mm (4 in), the leakage becomes equal to the leakage rate with no geomembrane at all (indicates that leakage flows laterally and reaches the wall of the perı meter with no head loss). The effect of the geotextile for hole diam less than 50 mm (2 in) is confirmed by pressure measurements in the soil in the case of a 20 mm (0·75 in) diameter geomembrane hole, which show that the water pressure on the soil surface (i.e. under the geotextile) was roughly uniform and one order of magnitude smaller than the uniform pressure in the case without geotextile between the geomembrane and soil.

Comparison between tests with and without geotextile. A larger geomembrane hole diameter is necessary with a geotextile (100 mm (4 in)) than without a geotextile (20 mm (0·75 in)) for the radial flow to reach the walls of the 1·5 m (5 ft) diameter permeameter. In cases where the radial flow does not reach the walls of the permeameter, the leakage rate with a geotextile is approximately one order of magnitude less than the leakage rate without a geotextile.

These observations are valid only for the considered materials and water pressures.

Interpretation of the tests. It may be concluded that, in the tests with a geotextile between the geomembrane and soil, geomembrane, geotextile and soil stayed in close contact when the geomembrane hole was smaller than 50 mm (2 in). The fact that water pressure on the soil was one order of magnitude less with than without geotextile confirms this interpretation, because:

- if water had accumulated *between the geomembrane and geotextile*, the water pressure on the soil would have been uniformly high, almost equal to the water pressure on the geomembrane (i.e. 200 or 400 kPa (4000 or 8000 psf)) since geotextile permittivity (i.e. permeability/thickness) is much larger than soil permittivity and, therefore, the head loss through the geotextile would have been small; and
- if water had accumulated *between the geotextile and soil*, both the geotextile and the geomembrane would have been uplifted and the water pressure on the soil would have been equal to the water pressure on the geomembrane (i.e. 200 or 400 kPa (4000 or 8000 psf)).

Tentative explanation. The case of a geomembrane alone is discussed first. Then the case where a geotextile is located between the geomembrane and the soil is compared to the former case to explain why the geomembrane, geotextile and soil stayed in close contact in some tests, thereby resulting in a smaller leakage rate with geotextile than without.

If the geomembrane is alone (i.e. if there is no geotextile between the geomembrane and the soil), the water pressure on top of the geomembrane is higher than the water pressure under the geomembrane if the geomembrane is in close contact with the soil. In fact, geomembranes are never in close contact with the soil (with the possible exception of geomembranes sprayed directly onto the soil) because of small soil surface irregularities that are bridged by the geomembrane. (This has been shown by Brown *et al.* using model tests (see Section 3.3.2), and this is even more true in the field where conditions are not as good as in model tests.) As a result, there are preferential paths for the water between the geomembrane and soil. Consequently, water pressure between geomembrane and soil quickly becomes equal to water pressure on top of the geomembrane, even in the case of leakage through relatively small geomembrane holes. Under ideal conditions, if the soil surface were perfectly smooth, and if the geomembrane had no wrinkles, there would be no preferential path for the water. As a result, the geomembrane and the soil would stay in close contact under the pressure applied by the water (approximately the same way two pieces of polished steel stick to each other because there is no air or water pressure between them).

If there is a geotextile between the geomembrane and soil, if the geotextile is thick enough and compliant enough to fill the irregularities in the soil surface, if the water pressure on top of the geomembrane is large, and if the geomembrane is flexible and placed without wrinkles (all requirements which were met in the experiments conducted by Fukuoka), then there is no preferential path for flow between geotextile and soil or between geotextile and geomembrane. Water then flows in the geotextile with pressure loss, since the geotextile is a porous medium. As a result, the pressure on top of the geomembrane is greater than the pressure underneath it. Consquently, the geomembrane is pressed against the geotextile and the soil.

The above mechanisms are supported by comparing the test discussed above, where geomembrane and geotextile are on a rather smooth surface, with a similar test conducted by Fukuoka using a geomembrane and a geotextile located on a soil surface that had been roughened by placing gravel on top of the soil. In the latter case, the discharge of water is the same as if there was no geotextile between the geomembrane and soil. This supports the view that the geotextile is effective in reducing flow rates only when it can prevent the formation of preferential flow paths at the soil–geotextile interface as well as the geotextile–geomembrane interface (the latter requirement would be fulfilled if the geotextile were glued or otherwise attached to the geomembrane, which was not the case in the tests discussed in this paper). The conditions to achieve this goal are:

- small hole in the geomembrane;
- soil surface as smooth as possible;
- thick and compliant geotextile, with no hole;

- flexible geomembrane, laid without wrinkles; and
- high pressure on the geomembrane (a liquid pressure being preferable to a solid overburden pressure because it is more uniform).

The final requirement is essential and may explain why no significant beneficial effect of geotextile was observed by Brown *et al.* who operated with small hydraulic heads acting on the geomembrane. The requirements for a smooth soil surface and a geomembrane without wrinkles may be difficult to fulfill in the field; therefore it is likely that, in many field conditions, a geotextile placed between a geomembrane and the underlying low-permeability soil will not decrease the leakage rate but may instead increase it as explained in Section 1.3.4.

It is interesting to note that the geotextile used in the tests was made from polyester, which is not a hydrophobic polymer like polypropylene. Therefore, the beneficial effect of the geotextile between the geomembrane and the low-permeability soil cannot be explained by water repulsion.

Lastly, the reader is reminded that the explanation presented above is only tentative. More testing is required to fully investigate the influence on leakage rate of a geotextile placed between a geomembrane and a low-permeability soil layer.

3.4 Conclusions on leakage through composite liners

3.4.1 Conclusions from analytical studies

It appears that the theoretical analyses involved in the apparently simple problem of leakage through a hole in a geomembrane placed on a low-permeability soil are extremely complex.

If perfect contact between the geomembrane and soil is considered, the two-dimensional problem has been solved but the three-dimensional problem still requires work. However, there are approximate solutions, which give valuable information.

If the contact between the geomembrane and soil is not perfect or if there is a geotextile between the geomembrane and soil, the liquid that has passed through a hole in the geomembrane flows laterally in the space between the geomembrane and the underlying soil ('interface flow'). Differential equations have been proposed to evaluate the leakage rate through a geomembrane hole when there is interface flow, which is almost always the case under field conditions. To use these equations, it is necessary to know the spacing between the geomembrane and the underlying low-permeability soil. The spacing depends on the quality of contact between the geomembrane and soil. Guidance has been provided in

Section 3.3.2 regarding spacing values which are assumed to represent excellent field conditions. Using these spacing values, approximate solutions have been proposed for the differential equations.

3.4.2 Conclusions from model tests

In all cases where a geomembrane is placed in direct contact with a low-permeability soil, tests show that the liquid which passes through a geomembrane hole flows laterally in the space between the geomembrane and the underlying soil before flowing into the soil. Such lateral flow occurs even under high overburden pressures which tend to press the geomembrane against the underlying soil. Tests show that, as a result of lateral flow, leakage rates are significantly greater than the leakage rates that would be obtained if there was perfect contact between the geomembrane and the underlying soil. The degree of contact between the geomembrane and soil in the model tests can be considered excellent (smooth soil surface, no cracks in soil) but not perfect since flow takes place between the geomembrane and the soil.

Tests show that (somewhat unexpectedly) a needlepunched nonwoven geotextile between the geomembrane and the soil decreases the leakage rate if the pressure on the geomembrane is high enough to push the geotextile into soil irregularities, thereby preventing free lateral flow between geomembrane and soil. In the field, this beneficial effect of geotextiles may be effective only in a limited number of cases where the following conditions are met: (i) the soil surface is very smooth; (ii) the geomembrane is very flexible and has no significant wrinkles; (iii) a thick, uniform and compliant geotextile is used; and (iv) overburden pressures are high and distributed uniformly. (Of course, the geotextile must not have a hole under the geomembrane hole and must not be connected to an outlet, as discussed in Section 1.3.4.) More research is needed before it is possible to recommend the use of a geotextile as a means to improve contact between the geomembrane and soil and thereby decrease the leakage rate.

Lessons learned from the model tests regarding flow of liquid between the geomembrane and soil are useful from a design and construction standpoint:

- From a design standpoint, it is necessary to take into account the flow of liquid between the geomembrane and the soil for leakage evaluations as well as for any other appropriate design considerations, such as soil softening, erosion, or solutioning caused by liquid flowing in the space between the geomembrane and the underlying soil layer.
- From a construction standpoint, it is recommended that every effort be made to develop good contact between geomembrane and low-

permeability soil. These efforts can include: (i) constructing the low-permeability soil layer with a smooth surface and no cracks; and (ii) preventing or eliminating wrinkles in the geomembrane. As an attempt at improving contact quality, the geomembrane could be sprayed onto the low-permeability soil instead of being produced in a plant and transported to the site: in this case, the contact may be nearly perfect.

Although the tests provide a good understanding of the flow mechanisms involved, the diameters of the permeameters used by Brown *et al.* and, to a lesser extent, by Fukuoka, were too small to give results which can be used directly for leakage rate evaluations. However, the extrapolation of test data, which was done by Brown *et al.* using a sound theoretical analysis, provides information which can be used to evaluate leakage in areas larger than the test permeameter.

In spite of their limitations, the tests show that composite liners are significantly more effective than either low-permeability soil liners or geomembrane liners. However, the test results also indicate that composite liners as they are usually built (i.e. by unrolling a geomembrane on a layer of low-permeability soil) do not perform as well as an ideal composite liner, which would be made of a geomembrane in perfect contact with a low-permeability soil (i.e. a geomembrane sprayed on the soil).

3.4.3 Conclusions for leakage rate evaluation

Review of methods for leakage rate evaluation. Several methods have been presented for the evaluation of the leakage rate through a composite liner due to a hole in the geomembrane component of the liner. These methods are summarized in Table 9 and can be ranked as follows:

- An *absolute minimum* of the leakage rate is obtained by assuming perfect contact between the geomembrane and the underlying soil and vertical flow (Fig. 5(c) and eqn (27)). In this case, the radius of the wetted area is obviously equal to the radius of the geomembrane hole.
- An *approximate value* of the leakage rate for the case of perfect contact between the geomembrane and the underlying soil is given by eqn (30).
- Leakage rates given by eqn (51), which combines theoretical analyses with experimental data from Brown *et al.*,[9] are assumed to correspond to *excellent field conditions*, as discussed in Section 3.3.2.
- Finally, leakage through a hole in a geomembrane alone (i.e. with nothing underneath it) is certainly much larger than leakage through a composite liner with the same geomembrane hole, even under field conditions with far from perfect contact between the geomembrane

TABLE 9
Summary of Equations Related to Leakage Through Composite Liners

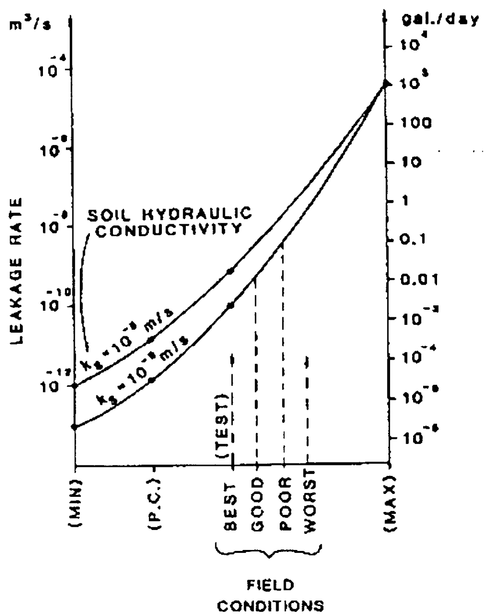
Absolute minimum	(MIN) in Figs 12 and 13
(Vertical flow)	
$Q = k_s a(h_w + H_s)/H_s$	(eqn (27))
$R = d/2$	
Perfect contact	(P.C.) in Figs 12 and 13
(Approximate value of Q given by radial flow)	
$Q = \pi k_s h_w d$	(eqn (30))
R = unknown	
Excellent contact	(BEST) in Figs 12 and 13
(Empirical equations from model tests)	
$Q = 0{\cdot}7\, a^{0{\cdot}1} k_s^{0{\cdot}88} h_w$	(eqn (51))
$R = 0{\cdot}5\, a^{0{\cdot}05} k_s^{-0{\cdot}06} h_w^{0{\cdot}5}$	(eqn (52))
Absolute maximum	(MAX) in Figs 12 and 13
(Free flow resulting from large space between geomembrane and soil)	
$Q = C_B a\sqrt{2gh_w} = 0{\cdot}6a\sqrt{2gh_w}$	(eqn (22))
$R = 0{\cdot}39 d(2gh_w)^{0{\cdot}25} k_s^{-0{\cdot}5}$	(eqn (55))

These equations give the leakage rate, Q, and radius of wetted area, R, for composite liners when there is a hole in the geomembrane. (The wetted area is the area of soil underneath the geomembrane that is wetted by the liquid flowing laterally between the geomembrane and soil prior to seeping into the soil.) The symbols used above are: k_s = hydraulic conductivity of low-permeability soil underlying the geomembrane; a = area of hole in geomembrane; h_w = liquid depth on geomembrane; H_s = thickness of soil layer; d = diameter of hole in geomembrane; and g = acceleration due to gravity. Basic SI units are: Q (m^3/s), R (m), k_s (m/s), a (m^2), h_w (m), H_s (m), d (m), and g (m/s^2). These units are mandatory for the two empirical equations.

and the underlying soil. This case, therefore, provides an *absolute maximum* of the leakage rate. The leakage rate through a hole in a geomembrane alone is given by Bernoulli's equation (eqn (22)).

From the above review of methods, it appears that the leakage rate in the case of actual field conditions will be between the value given by eqn (51) (excellent field conditions) and the value given by eqn (22) (absolute maximum). Interpolation between these two values can be done using the 'leakage rate graph', as discussed below.

Leakage rate and radius graphs. Because of the uncertainties in the analyses as well as the wide variety of contact conditions, it is appropriate in each given case to plot leakage rates obtained with all the methods described above in order to make interpolations. It is also appropriate to use a semi-logarithmic scale for the plot since leakage rates vary within a range of several orders of magnitude, as is usually the case in hydraulic problems. The graph in Fig. 12 has been established with a 1 cm^2 (0·16 in^2) hole, which is one of the two holes (i.e. the large hole) recommended for



ig. 12. Graph giving the leakage rate due to a geomembrane hole in a composite liner. The quid depth on the liner is 30 mm (0·1 ft), the hole area is 1 cm^2 (0·16 in^2) (i.e. diameter of 1·3 mm), and the soil layer thickness is 0·9 m (3 ft). Field conditions can be anywhere etween the two extremes: (1) best, i.e. the soil is well compacted, flat and smooth, has not een deformed by rutting during construction, and has no clods and cracks, and the eomembrane is flexible and has no wrinkles, and the geomembrane and soil are in close ontact; and (2) worst, i.e. the soil is poorly compacted, has an irregular surface and is racked, and the geomembrane is stiff and exhibits a pattern of large, connected wrinkles. Abbreviations: GOOD and POOR = good and poor field conditions; MIN, P.C., TEST, nd MAX are defined in Table 9. The points correspond to numerical values given in Table 10 and the curves were interpolated between these points.

lesign, as indicated in Section 2.3.9. This graph has been established for a iquid depth of 30 mm (0·1 ft). Numerical values used to establish the graph in Fig. 12 are given in Table 10.

Similarly, a graph can be established for the radii of wetted areas (i.e. he area covered by leakage flowing between the geomembrane and the ow-permeability soil, before it flows into the soil) obtained with all the nethods described above and summarized in Table 9. The radius graph corresponding to a liquid depth of 30 mm (0·1 ft) is given in Fig. 13. Numerical values used to establish the graph in Fig. 13 are given in Table 10.

Similar graphs have been established for liquid depths ranging between 0·003 m (0·01 ft) and 30 m (100 ft). These graphs are not given here. Since Eqns (51) and (52) are less valid for liquid depths larger than approximate-

TABLE 10
Numerical Values Used to Establish the Graphs Presented in Figs 12 and 13

	Case	Equation	Hydraulic conductivity of soil underlying the geomembrane, k_s		
			10^{-9} m/s	*10^{-8} m/s*	*10^{-7} m/s*
Leakage rate Q (m^3/s)	Absolute minimum	27	$1{\cdot}0 \times 10^{-13}$	$1{\cdot}0 \times 10^{-12}$	$1{\cdot}0 \times 10^{-11}$
	Perfect contact (approximate theory)	30	$1{\cdot}1 \times 10^{-12}$	$1{\cdot}1 \times 10^{-11}$	$1{\cdot}1 \times 10^{-10}$
	Excellent contact (model tests)	51	$1{\cdot}0 \times 10^{-10}$	$7{\cdot}6 \times 10^{-10}$	$5{\cdot}8 \times 10^{-9}$
	Free flow (Bernoulli's equation)	22	$4{\cdot}6 \times 10^{-5}$	$4{\cdot}6 \times 10^{-5}$	$4{\cdot}6 \times 10^{-5}$
Radius of wetted area R (m)	Absolute minimum (hole radius)	$R = d/2$	0·005 6	0·005 6	0·005 6
	Perfect contact (unknown)		≈0·032[a]	≈0·032[a]	≈0·032[a]
	Excellent contact (model tests)	52	0·19	0·17	0·14
	Free flow (Bernoulli's equation)	55	122	38	12

[a]Value obtained by interpolation in Fig. 13.
This table has been established for a liquid depth of 30 mm (0·1 ft) on top of the geomembrane, a hole area of 1 cm^2 (0·16 in^2), and a low-permeability soil thickness of 0·9 m (3 ft).

ly 1 m (3 ft), interpolations between eqns (22) and (30) were necessary for establishing the graphs related to 3 m and 30 m (10 ft and 100 ft) liquid depths. This further emphasizes the appropriateness of the graphical approach.

Use of the leakage rate graph. The leakage rate graph permits the determination of the leakage rate for any given field condition by interpolation between the best case and the worst case:

- In the best case: (i) the soil is well compacted, flat and smooth, has not been deformed by rutting due to construction equipment, and has no clods nor cracks; (ii) the geomembrane is flexible and has no wrinkles; and (iii) the geomembrane and the soil are in close contact.
- In the worst case: (i) the soil is poorly compacted, has an irregular surface, and is cracked; and (ii) the geomembrane is stiff and exhibits a pattern of large, connected wrinkles.

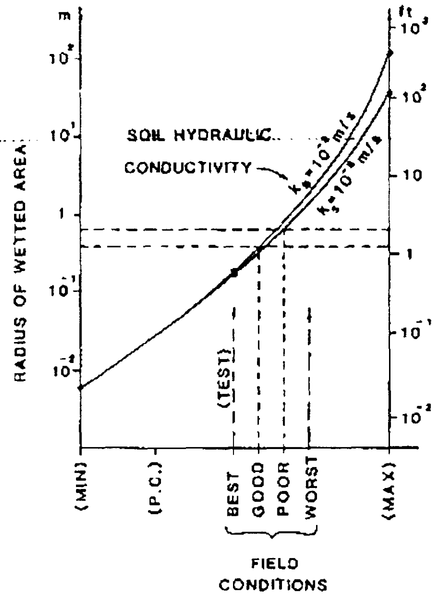


Fig. 13. Graph giving the radius of the wetted area due to a geomembrane hole in a composite liner. The liquid depth on the liner is 30 mm (0·1 ft) and the hole area is 1 cm^2 (0·16 in^2) (i.e. diameter of 11·3 mm), and the soil layer thickness is 0·9 m (3 ft). Field conditions can be anywhere between the two extremes: (1) best, i.e. the soil is well compacted, flat and smooth, has not been deformed by rutting during construction, and has no clods and cracks, and the geomembrane is flexible and has no wrinkles, and the geomembrane and soil are in close contact; and (2) worst, i.e. the soil is poorly compacted, has an irregular surface and is cracked, and the geomembrane is stiff and exhibits a pattern of large, connected wrinkles. Abbreviations: GOOD and POOR = good and poor field conditions; MIN, P.C., TEST, and MAX are defined in Table 9. The points correspond to numerical values given in Table 10 and the curves were interpolated between these points.

Location of the best and worst cases on the graphs. In order to interpolate between the best case and the worst case, it is necessary to locate these two cases on the graphs.

The *best field case*, as it is described above, appears to be almost as good as the conditions in the tests by Brown *et al.* and Fukuoka presented in Section 3.3. (In fact, in Section 3.3.2, we indicated that eqns (51) and (52) derived from Brown *et al.*'s tests are assumed to correspond to 'excellent field conditions'.) Therefore, on the graphs, the best case for field conditions is represented by a vertical line corresponding to the test results.

The *worst field case* has been located on the leakage rate graph using the following procedure. We have assumed that the radius of the wetted area cannot exceed a value of the order of 30 m (100 ft) for soil hydraulic conductivity of 10^{-8} m/s (10^{-6} cm/s), a liquid depth of 30 m (100 ft), and a hole area of 1 cm^2 (0·16 in^2). Using the radius graph (not shown here) related to a 30 m (100 ft) liquid depth and a 1 cm^2 (0·16 in^2) hole, we found that this assumption led to a worst case line approximately halfway between the 'best case' and the 'absolute maximum' leakage rate case. For the sake of simplicity, we decided to place the worst case line exactly halfway between the best case and the absolute maximum leakage rate case on all leakage rate graphs. The location of the worst case line thus obtained is far from the absolute maximum (free flow through holes in the geomembrane), which is an extremely unlikely case.

Good and poor field conditions. On Fig. 12, we have arbitrarily divided the space between the best field case and the worst field case in thirds and we have thus obtained a vertical line representing *good field conditions* and a vertical line representing *poor field conditions*. As a result, it appears in Fig. 12 that, for a liquid depth of 30 mm (0·1 ft), a 1 cm^2 (0·16 in^2) geomembrane hole, and a soil hydraulic conductivity of 10^{-9} m/s (10^{-7} cm/s), a leakage rate of 0·07 liters/day (0·02 gallons/day) corresponds to good field conditions, whereas a leakage rate of 0·4 liters/day (0·1 gallons/day) corresponds to poor field conditions.

3.4.4 Conclusions on the role of overburden pressure

Influence of overburden pressure on leakage rate. Tests and theoretical analyses have shown that the leakage rate through a geomembrane hole increases as the interface flow increases. (Interface flow is the flow between the geomembrane and underlying soil.) Interface flow increases with increasing values of the spacing between the geomembrane and underlying soil. Overburden pressure tends to decrease this spacing. As discussed in Section 3.3.2, tests by Brown *et al.*[9] have shown marked decreases in leakage rates when the overburden pressure increased from 1·5 to 160 kPa (30–3340 psf). However, these tests were conducted under laboratory conditions, with a geomembrane laid flat on a smooth soil layer, and it is premature to draw firm conclusions regarding the role of overburden pressures in the field. Nonetheless, it is possible to crudely take into account the overburden pressure in leakage rate calculations. This can be achieved in the selection of the field-condition abscissa in the leakage rate graph (Fig. 12). For instance, for a properly designed and constructed facility that has undergone a rigorous construction quality assurance program (so that the soil is well compacted and smooth and geomembrane wrinkles are small), a 'best' field-condition abscissa could be considered if the overburden pressure is high, instead of 'good' if the overburden pressure is low.

Role of overburden pressure in liquid impoundments. As discussed in Section 3.4.3, the radius of the wetted area in the case of large liquid depths corresponding to liquid impoundments (lagoons, reservoirs, dams) can be of the order of up to 30 m (100 ft) depending on the hydraulic conductivity of the soil and the quality of the contact between the geomembrane and the soil. In other words, the large leakage rates in the case of liquid impoundments correspond to large wetted areas. Therefore, an overburden pressure on the geomembrane component of a liquid impoundment composite top liner can be very beneficial since it will impede lateral flow between geomembrane and underlying soil, thereby decreasing leakage. It is preferable that the overburden be provided by a soil with fine particles, which may further decrease the leakage rate by clogging the geomembrane holes. (It should also be kept in mind that an overburden pressure on the composite top liner of a liquid impoundment is necessary to prevent geomembrane uplift, as discussed in Section 1.3.7.)

3.4.5 Conclusions on rate of leakage through composite liners

Unitized leakage rates through composite liners due to holes in the geomembrane, obtained from Fig. 12 (liquid depth of 30 mm (0·1 ft) and 1 cm^2 (0·16 in^2) hole area), and similar graphs for other liquid depths and

TABLE 11
Calculated Unitized Leakage Rates Through Composite Liners

		Liquid depth on top of the geomembrane, h_w				
Field conditions	*Leakage mechanism*	*0·003 m (0·01 ft)*	*0·03 m (0·1 ft)*	*0·3 m (1 ft)*	*3 m (10 ft)*	*30 m (100 ft)*
Good	Permeation	0·000 1	0·01	1	100	300
	Small hole	0·02	0·15	1	9	75
	Large hole	0·02	0·2	1·5	11	85
Poor	Permeation	0·000 1	0·01	1	100	300
	Small hole	0·1	0·8	6	50	400
	Large hole	0·1	1	7	60	500
		Values of unitized leakage rate in lphd (figures to be divided by approximately 10 to obtain values expressed in gpad)				

Unitized leakage rates are leakage rates per unit area of liner. Leakage due to permeation is obtained from Table 7 and leakage due to holes is obtained from Fig. 12 and similar graphs as a function of the field conditions defined in Fig. 12. (All results have been rounded up.) This table has been established with: hole frequency = 1 per 4000 m^2 (1 per acre); small hole area = 3·1 mm^2 (0·005 in^2); large hole area = 1 cm^2 (0·16 in^2); soil thickness = 0·9 m (3 ft); soil hydraulic conductivity 10^{-9} m/s (10^{-7} cm/s); and HDPE geomembrane thickness = 1 mm (40 mils). The liquid depths used here correspond to the typical values defined in Section 1.3.6. (Note: As indicated before eqn (45), the method used is unconservative for large hydraulic heads and may underestimate leakage rates for liquid depths greater than 0·3 m.)

hole areas, are summarized in Table 11, which also gives unitized leakage rates due to permeation obtained from Table 7. Although Table 7 was established for a geomembrane alone, unitized leakage rates due to permeation from Table 7 can be used for composite liners since leakage rates due to permeation should not be significantly affected by the underlying soil because all soils are very pervious as compared to geomembranes. Table 11 was established using a geomembrane defect (hole) frequency of 1 per 4000 m^2 (1 per acre). This frequency is based on the results presented in Section 2.3.7.

Table 11 summarizes our best judgement on leakage rates through composite liners. This table shows that leakage rates through composite top liners can be much larger in the case of liquid impoundments (where the hydraulic head acting on the top liner is usually large) than in the case of facilities storing solids such as landfills or ore leach pads (where the hydraulic head acting on the top liner is usually small). It also shows that leakage through composite bottom liners (subjected to liquid depths ranging from zero to 0·03 m (0·1 ft)) can be very small. This latter observation emphasizes the merit of double liner systems with composite bottom liners for applications (such as pollution control) requiring a very high level of liquid containment.

4 CONCLUSIONS

Conclusions on leakage through liners constructed with geomembranes are drawn hereafter from the review of theoretical analyses, laboratory tests, and field data presented in this paper. These conclusions must be considered tentative since additional research is needed. However tentative, these conclusions should be useful to the many engineers presently involved in the analysis and design of geomembrane-lined facilities.

4.1 Defects and quality assurance

Even with intensive quality assurance, it is reasonable to expect 3–5 geomembrane defects per hectare (one or two defects per acre). Most of these defects are caused by inadequate seaming. In addition, there may be geomembrane defects caused by puncture, tear, excessive stresses, etc. Defects may also be due to inadequate geomembrane connections to sumps, pipe penetrations, and other appurtenances, which are often problem areas. Also, the geomembrane may undergo excessive stresses in the vicinity of connections, which may cause defects to develop after the geomembrane is in service.

The leakage rate values, which are summarized in Table 12, were obtained assuming 3 geomembrane defects per hectare (one defect per acre) which implies that: (i) intensive quality assurance is provided; (ii) extreme care is taken at geomembrane connections to sumps, pipe penetrations, and other appurtenances; and (iii) an excellent design minimizes the risk of excessive stresses, which could generate very large holes.

TABLE 12
Unitized Leakage Rates Through Liners

Type of liner	*Leakage mechanism*	*Liquid depth on top of the geomembrane, h_w* 0·003 m (0·01 ft)	0·03 m (0·1 ft)	0·3 m (1 ft)	3 m (10 ft)	30 m (100 ft)
Geomembrane alone (between two pervious media)	Permeation	0·000 1	0·01	1	100	300
	Small hole	100	300	1 000	3 000	10 000
	Large hole	3 000	10 000	30 000	100 000	300 000
Composite liner (good field conditions)	Permeation	0·000 1	0·01	1	100	300
	Small hole	0·02	0·15	1	9	75
	Large hole	0·02	0·2	1·5	11	85
Composite liner (poor field conditions)	Permeation	0·000 1	0·01	1	100	300
	Small hole	0·1	0·8	6	50	400
	Large hole	0·1	1	7	60	500

Values of leakage rate in lphd (figures to be divided by approximately 10 to obtain values expressed in gpad)

This table has been obtained by combining Tables 7 and 11. The small hole has a surface area of 3·1 mm^2 (0·005 in^2). The large hole has a surface area of 1 cm^2 (0·16 in^2). The frequency of holes is 1 per 4000 m^2 (1 per acre). The thickness of the soil layer is 0·9 m (3 ft) and its hydraulic conductivity is 10^{-9} m/s (10^{-7} cm/s). The HDPE geomembrane thickness is 1 mm (40 mils). The liquid depths used here correspond to the typical values defined in Section 1.3.6. Field conditions are defined in Fig. 12. Leakage rates in the case of a composite liner do not significantly depend on the material overlying the geomembrane. In the case of a geomembrane alone, leakage rates were calculated assuming that the geomembrane is overlain and underlain by an infinitely pervious medium. This assumption is valid for coarse gravel or geonet. Leakage rates through holes would be significantly less if the geomembrane were overlain and/or underlain by sand or a less permeable material.

4.2 Summary of leakage rate values

Table 12 summarizes unitized leakage rates through liners. This table ha been obtained by combining Table 7 for geomembranes alone with Tabl 11 for composite liners. This table represents our best judgement regard ing rates of leakage through liners under steady-state, saturated flo conditions.

This table has been established with the following assumptions:

- The geomembrane is 1 mm (40 mil) thick and has one hole pe 4000 m^2 (acre) with a surface area of either 1 cm^2 (0·16 in^2), o 3·1 mm^2 (0·005 in^2).
- The low-permeability soil layer underlying the geomembrane has a thickness of 0·9 m (3 ft) and a hydraulic conductivity of 1×10^{-9} m/s (1×10^{-7} cm/s).
- The material on top of the geomembrane is very permeable and does not impede flow through geomembrane defects.

The liquid depths used in Table 12 represent the following conditions:

- 0·003 m (0·01 ft) is representative of the case of a synthetic drainage layer; it is the liquid depth on the bottom liner if a synthetic drainage layer is used as a leakage collection layer, and the liquid depth on the top liner of a facility containing solids if the synthetic drainage layer is used as a leachate collection layer.
- 0·03 m (0·1 ft) is assumed to be an average liquid depth on the top liner of a landfill with a well-designed and constructed granular leachate collection layer; this is also a conservative value for the liquid depth on the bottom liner of any double liner system.
- 0·3 m (1 ft) is the maximum liquid depth on the top liner of a landfill typically considered in the design of a granular leachate collection layer for waste disposal facilities in the USA.
- 3 m (10 ft) is a typical liquid depth on the top liner of a shallow surface impoundment (storage of chemical liquids, small water reservoirs, canals).
- 30 m (100 ft) is a typical liquid depth in deep water reservoirs and dams.

4.3 Comments on leakage rate values

4.3.1 Leakage through top liners

Geomembrane top liner. It appears from Table 12 that unitized leakage rates through geomembrane top liners (geomembrane alone) underlain and overlain by very pervious media are high if there is one hole per

4000 m^2 (acre) in the geomembrane. Assuming one small hole per 4000 m^2 (acre) under actual operating conditions results in leakage rates of the order of 100–1000 lphd (10–100 gpad) in solids storage facilities (such as landfills) and 3000–10 000 lphd (300–1000 gpad) in liquid impoundments. If the geomembrane is punctured or has a large hole due to defective design or construction, much larger leakage rates could be experienced, as evidenced by the leakage rate values corresponding to a large hole in Table 12. Since it is impossible to guarantee that there will be no hole in a geomembrane, relatively large leakage rates should be considered during design. The use of a composite top liner should be considered in cases where leakage through the top liner must be minimized.

It is important to remember that the above comments are based on leakage rate values calculated in the case of a geomembrane placed between two very pervious media such as geonets or coarse gravels. Smaller leakage rates would be obtained if the geomembrane was overlain and/or underlain by sand. The authors have undertaken a study to determine the reduction in leakage rates through a geomembrane hole achieved by placing sand on top of and/or underneath the geomembrane. It is also important to remember that the leakage rates discussed above were calculated assuming steady-state, saturated flow conditions.

Composite top liner in a landfill. It appears in Table 12 that, in the case of a composite liner, there is no significant difference in leakage rate between the small hole (d = 2 mm = 0·08 in) and the large hole (d = 11·3 mm = 0·45 in). Table 12 shows that unitized leakage rates through a composite top liner in the case of a landfill can be small, i.e. less than 10 lphd (1 gpad) if the liquid depth on top of the geomembrane is 0·3 m (1 ft), which normally occurs only during short periods of time, and of the order of 0·1–1 lphd (0·01–0·1 gpad) if the liquid depth on top of the geomembrane is 0·003–0·03 m (0·01–0·1 ft), which is more likely to be the range of the average liquid depth over a long period of time. However, it should be kept in mind that these low leakage rates can be achieved only if the lining system is constructed with intensive quality assurance and if the geomembrane is not subjected to excessive stresses likely to cause a large breach. It should also be kept in mind that construction of top composite liners (i.e. construction on top of the leakage collection layer and bottom liner) is relatively difficult. Therefore, it may not always be possible to obtain a value of hydraulic conductivity as low as 10^{-9} m/s (10^{-7} cm/s) for the soil component of a composite top liner. A hydraulic conductivity of 10^{-8} m/s (10^{-6} cm/s) may be more realistic in some cases, which would increase by a factor of approximately 5 the unitized leakage rate values given above (which were obtained with $k_s = 10^{-9}$ m/s (10^{-7} cm/s)).

It is important to remember that, in the case of a composite liner, leakage rates are not significantly affected by the material overlying the geomembrane, provided that the hydraulic conductivity of the overlying material is greater than that of the low-permeability soil component of the composite liner. Since the overlying material is almost always more permeable than the low-permeability soil component, it may be concluded that, for all practical purposes, the above results are valid regardless of the material overlying the geomembrane component of the composite top liner. It is also important to remember that the leakage rates discussed above were calculated assuming steady-state, saturated flow conditions.

Composite top liner in a liquid impoundment. Table 12 also shows that, even with a composite top liner, the unitized leakage rate in the case of liquid impoundments may remain high, e.g. 100–800 lphd (10–80 gpad). (These values, established for a hydraulic conductivity of the soil component of the top liner $k_s = 10^{-9}$ m/s (10^{-7} cm/s), would be approximately 5 times greater if $k_s = 10^{-8}$ m/s (10^{-6} cm/s).) As indicated in Section 3.4.4, leakage rates can be decreased if the geomembrane is covered with a layer of soil, preferably a soil with fine particles. It also appears that unitized leakage rates due to permeation through the geomembrane may not be negligible in the case of liquid impoundments; however, additional research is needed in this area before firm conclusions are drawn.

4.3.2 Leakage through bottom liners

The depth of liquid on the bottom liner of a double-liner system is small in well-designed and constructed facilities. As indicated in Section 1.3.6, typical values of the liquid depth *for design* are in the range of 0·003 m (0·01 ft) to 0·03 m (0·1 ft). The 'for design' is emphasized because liquids that leak through the top liner flow only in a small fraction of the leakage collection layer; consequently, these liquid depths exist only on a small fraction of the bottom liner. Using these design liquid depths, Table 12 shows that unitized leakage rates through a well-constructed composite bottom liner can be anywhere between 10^{-4} lphd (10^{-5} gpad) and 0·2 lphd (0·02 gpad), depending on the coincidence of the wetted portion of the leakage collection layer and the bottom liner geomembrane defects. The probability for such coincidence is small if the number of geomembrane defects is small (e.g. one hole per 4000 m^2 (acre)).

Considering that the concentrations of pollutants in landfill leachates are typically relatively low, these leakage rate values should result in negligible pollutant discharges to the ground below the waste containment facility. The situation is improved further when attenuation of pollutants in the compacted soil component of the bottom liner is considered. Thus, it appears that properly designed, constructed and operated double liner systems with composite bottom liners can provide a very high level of environmental protection.

As indicated in Section 4.3.1 for the case of landfill composite top liners, the above leakage rate values are valid regardless of the material overlying the geomembrane component of the composite bottom liner.

4.4 Final comments

4.4.1 Comment on the state of practice

The tests and analyses presented in this paper show that composite liners as they are usually built (i.e. by unrolling a geomembrane on a layer of low-permeability soil) do not perform as well as an ideal composite liner, which would be made of a geomembrane in perfect contact with a low-permeability soil. However, leakage rate calculations show that composite liners are significantly more effective than either low-permeability soil liners or geomembrane liners.

4.4.2 Comments on the state of the art

The review of available data presented in this paper shows that a lot more needs to be known on the subject of leakage through liners: laboratory tests should be conducted on the permeation of water and other liquids through geomembranes; analytical and numerical studies on leakage through composite liners should be pursued; large-scale model tests on composite liners should be undertaken; and field data on the quality of installed liners should be collected and statistically analysed. The authors hope that this paper will stimulate research and generate a productive discussion in the profession.

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